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Jean-Christophe CAFFET, EUREQua

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Health Effects and Optimal Environmental Taxes in Welfare State Countries

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Résumé:

Les études consacrées à l'hypothèse de double dividende sont traditionnellement menées en équilibre général afin de mettre en évidence les effets d'interaction fiscale entre la taxe environnementale et les taxes pré-existantes. Pour la plupart, elles concluent que ces effets d'interaction (négatifs) annulent l'effet (positif) de recyclage du revenu fiscal environnemental, c'est à dire qu'une réforme fiscale environnementale accroît le coût social global du système fiscal, conduisant ainsi au rejet de l'hypothèse de double dividende. En conséquence, le taux optimal de taxation de la pollution est égal au ratio du taux Pigouvien (dommages marginaux) sur le coût marginal des fonds publics. Cet article revient sur ces conclusions en soulignant les effets positifs sur la santé et l'offre de travail des ménages que l'on peut vraisemblablement attendre de l'élaboration d'une fiscalité environnementale. En intégrant l'existence d'un système de protection sociale dans un modèle d'équilibre général classique, cet article montre que le taux de taxe optimale est supérieur à celui traditionnellement mis en évidence.

Mots-clefs : taxe environnementale, double dividende, emploi, santé, sécurité sociale.

Abstract:

Most studies on the green tax reform issue point out that environmental taxes exacerbate pre-existing tax distortions, thereby increasing the welfare costs associated with the overall tax code. As a result, the optimal environmental tax should lie below the Pigovian level (or marginal social damages). This article challenges this finding by arguing that health benefits from reduced pollution may sufficiently affect labor supply to create benefit-side tax interactions which, in turn, may be of the same magnitude as cost-side ones. Using a simple general equilibrium model that assumes the existence of a social security system, this paper shows that the optimal environmental tax rate could be greater than traditionally thought.

Key-Words : environmental tax, double dividend, employment, health, social security.

JEL Classification: D60, H21, H23, I18, J22, Q28

Introduction

Since the Rio Conference took place in 1992 and despite the failure of Kyoto Summit (1997), there has been a very extensive literature on the “environmental tax reforms” issue. If it is commonly accepted that government must intervene in regulating environmental externalities, it actually remains an open question to know what forms this intervention should rather take (taxes or quotas), and what we should expect from it in terms of economic efficiency. This last notion, now widely referred as to the “double dividend hypothesis”, is the key-point of the debate.

Tullock (1967) and Terkla (1984) were the first to suggest that revenues from environmental taxation could be used to finance reductions in preexisting taxes. This fund *recycling* process would significantly reduce the welfare costs associated with the overall tax code, compared to the case where environmental revenues are returned lump-sum. The double dividend hypothesis, in its strong form, claims that such a swap could generate a welfare gain, in other words that a well-calibrated environmental tax reform could have negative gross costs. The argument requires that the environmental tax raises revenue in a less distortionary way than the tax it replaces, so that there is a welfare gain associated with the tax swap, even if we ignore the environmental improvement. In particular, if the revenue obtained from environmental taxation were used to reduce taxation of labor, it would reduce the distortion in the labor market, thereby reducing the deadweight loss associated with income taxes. As a result, the double dividend hypothesis implies that the optimal environmental tax generally exceeds marginal damages when revenues are used in this way.

Despite the intuitive appeal of this notion, a literature developed in the 1990s which suggested that the ability to simultaneously curb pollution and tax distortions is much more limited than previously thought. Although the authors of this literature acknowledge the positive welfare effect of recycling environmental revenues through tax cuts, they also emphasize “second-best” negative impacts of pollution taxes. Armed with general-equilibrium models, they highlight previously unrecognized welfare costs related to *interactions* between the new tax and preexisting taxes : in a second-best world where labor is already taxed, environmental taxation, by driving up the price of (polluting) goods relative to leisure, tends to compound the distortions caused by taxes in labor markets and consequently

induces a welfare loss. This effect has become known as the *tax-interaction effect* and has been promoted by authors like Bovenberg and de Mooij (1994), Bovenberg and Van der Ploeg (1994), Parry (1996), Goulder (1995) or Goulder, Parry, Burtraw (1997) ... who furthermore claimed that this tax-interaction effect typically dominates the revenue-recycling effect. The main reason is that the environmental tax erodes the tax base (first dividend) and therefore requires a compensative increase in the labor tax rate, thus creating an efficiency loss¹: whereas environmental taxes were supposed to correct distortions in the labor market, they finally exacerbate them... As a result, the optimal rate of pollution taxation lies below marginal environmental damages in these BMPG (Bovenberg – de Mooij – Parry – Goulder) models, more precisely it is the ratio of the Pigovian rate divided by the Marginal Cost of Public Funds (MCPF).

In the late 1990s, authors like Kahn and Farmer (1999) or Schwartz and Repetto (2000) suggested that BMPG conclusions were essentially due to the underlying assumptions of their models². Relaxing the hypothesis of weak separability³ of environmental quality in the utility function or introducing the environment as a factor of production in BMPG models, they show that the tax interaction effect is reduced in magnitude and may even be offset if the improved environmental quality induces people to increase their labor supply by a sufficient amount. Regarding health impacts of air pollution⁴, Schwartz and Repetto (2000) finally assert that prospects for a double dividend are magnified as soon as separability assumptions are dropped.

¹ In other words : « there are more ways to “escape” paying the (environmental) tax because there are more things to substitute away to – the labor tax distorts the consumption/leisure decision, but the tax on the dirty good distorts the consumption/leisure decision *and* the choice between the clean and the dirty consumption good. Because the dirty good tax is more distorting than the wage tax, collecting an equivalent amount of revenue using the tax on the dirty good causes a higher deadweight loss and reduce the real output of the economy more than using the labor tax. In the context of a revenue-neutral swap between two taxes, the wage tax cannot be reduced enough to compensate for the effect on the real wage of the increased tax on the dirty good. Hence, the real wage, and thus non-environmental welfare, declines ». Employment, Environmental Taxes, and Income Taxes, N. Eissa, R. Blundell, L. Blow, Redefining Progress (May 2000).

² « We strongly believe these conclusions to be an artifact of the structure of the models which have been used to examine the double dividend (...). Although these assumptions make the models tractable, they do contribute to the primary findings of these papers », Schwartz and Repetto (2000).

³ Weak separability implies that environmental quality does not affect consumers’ trade-off between consumption and leisure.

⁴ Studies by Ostro (1994), Zuindema and Nentjes (1997) indicate that « decreasing levels of major air pollutants by about 30% will result in about three less work-loss days per worker ».

Explicitly modeling health impacts of air pollution in the utility function, Williams (2003) contradicts Schwartz and Repetto's intuitions and confirms that environmental taxation tends to exacerbate the distortions of the overall tax system. Incorporating both medical expenditures and time lost to sick-days in the respective household budget and time constraints, he demonstrates that there is actually a potential benefit-side tax-interaction effect from a green tax reform, but that this kind of positive interactions would certainly not offset negative ones, so that the double dividend hypothesis finally fails. His result is mainly due to the presence of an income effect related to the decrease of medical expenditures. This income effect leads households to allocate a large fraction of the additional time (less sick-days) to leisure, thus creating an efficiency loss. Furthermore, benefit-side tax interaction effects turn out to be negative with *typical* parameters, and what was initially thought to be a gain is finally costly...

It seems that we may criticize Williams' (2003) conclusions the same way he himself criticized Schwartz and Repetto's (2000) analysis⁵. If Williams (2003) sharply focuses on health effects and labor supply decisions, it nevertheless seems that he forgot a crucial variable to correctly examine the double dividend hypothesis. Indeed, Parry and Bento (2000) have showed that allowing tax deductible expenditures substantially reduces the costs of revenue-neutral environmental taxes. Since medical expenditures are at least partially returned to households in most developed countries, it seems that we should incorporate this kind of subsidies to better examine the double dividend hypothesis.

This paper is organized as follows. Section I presents a model, which is somewhat an extension of Williams (2003), to the extent that it develops a simple general-equilibrium model that incorporates a household labor-leisure decision along with a pollution externality. Following Parry and Bento (2000) intuitions and in order to estimate double dividend prospects within a more realistic framework, our model incorporates in addition subsidies to medical expenditures. More generally, a social security system is assumed, which consists in subsidies to medical expenditures and social transfers during sick-days. For simplicity we will suppose that households still get their gross wage during these work-loss days. Section II

⁵ In his abstract, Williams (2003) reproaches Schwartz and Repetto (2000) for not having explicitly modeled health impacts of air pollution. More precisely, he criticizes the fact that their fixed household time constraint does not take work-loss days into account. As a result, any decrease in what they call "enforced leisure" leads to an increase in labor supply.

examines the welfare effects of a green tax reform, in other words the welfare impacts of a revenue neutral swap between labor and environmental taxation. Then Section III highlights the level of the optimal environmental tax in a second-best setting where benefit-side tax interaction effects are *effectively* taken into account. Finally Section IV presents conclusions.

1. Model

We assume a representative agent maximizing his continuous and quasi-concave utility function given by :

$$U = U(C, D, l, G, H) \quad (1)$$

where C and D respectively represent the (aggregate) consumptions of clean and dirty goods, l the hours of leisure or non-market time, G the quantity of a public good and H the health condition of the agent.

As defined by Williams (2003), health condition is a function of both environmental quality Q and medical expenditures M :

$$H = H(M, Q) \quad (2)$$

$$\text{with } \frac{\partial H}{\partial Q} > 0, \quad \frac{\partial H}{\partial M} > 0 \quad \text{and} \quad \frac{\partial^2 H}{\partial M^2} < 0$$

We then choose the same linear pollution function, where \bar{Q} is an exogenous baseline level of environmental quality :

$$Q = \bar{Q} - D \quad (3)$$

The pollution externality associated with the consumption of the dirty good has two effects : first, it diminishes the consumer welfare by deteriorating his health condition. Second, it causes households to lose some time to sickness, thus reducing their time

endowment. As opposed to Williams (2003), these sick-days are not exclusively a function of environmental quality but more generally of the agent's general health condition :

$$S = S[H(M, Q)] \quad \text{with} \quad \frac{\partial S}{\partial H} < 0 \quad (4)$$

This new hypothesis is introduced not only because it seems more realistic, but also because it will allow us to better approach interactions between subsidies to medical expenditures and environmental taxation. Under this hypothesis, the household time constraint becomes :

$$L + l = T - S[H(M, Q)] \quad (5)$$

where T represents household's time endowment and L is time dedicated to labor, unique production factor in our model. We assume that the technology used exhibits constant returns to scale and units are normalized so that one unit of labor can produce one unit of any of the four goods :

$$F(L) = L = C + D + G + M \quad (6)$$

The initial tax code includes a tax on labor income t_L , a tax on the consumption of the polluting good t_D , and a social security system. This social security system both preserves the gross wage during sick-days, and grants subsidies to medical expenditures; for simplicity we assume a global subvention rate t_M . We also normalize the gross wage to equal one, yielding the following consumer budget constraint :

$$(1 - t_L)[L + S(H)] + I = C + (1 + t_D)D + (1 - t_M)M \quad (7)$$

where I is lump-sum income, which is assumed to be zero.

Government income is the sum of labor and pollution tax revenues. Therefore, government budget balance requires :

$$t_L [L + S(H)] + t_D D = G + t_M M + S(H) \quad (8)$$

Households maximize utility subject to their time and budget constraints, taking the quantity of the public good, the tax rates and the level of environmental quality as given. This yields the following first-order conditions, and then defines the uncompensated demand equations for the four goods :

$$\begin{cases} \frac{\partial U}{\partial C} = I \\ \frac{\partial U}{\partial D} = I (1 + t_D) \\ \frac{\partial U}{\partial l} = I (1 - t_L) \\ \frac{\partial U}{\partial H} = I (1 - t_M) \frac{\partial M}{\partial H} \end{cases} \quad \begin{cases} C(t_D, t_L, t_M, Q, I) \\ D(t_D, t_L, t_M, Q, I) \\ l(t_D, t_L, t_M, Q, I) \\ M(t_D, t_L, t_M, Q, I) \end{cases}$$

where I is the marginal utility of income.

2. Welfare effects of a green tax reform.

This section examines impacts on welfare of a change in the environmental tax rate. To obtain the same kind of relation BMPG models usually achieve, we introduce the following key-parameter :

$$h = \frac{t_L \frac{\partial l}{\partial t_L}}{L + S(H) - t_L \frac{\partial l}{\partial t_L}} + 1 \quad (9)$$

This is the marginal cost of public funds (MCPF), the cost to the household of raising a marginal dollar of government revenue through the labor tax. The numerator of the first term is the welfare loss from an incremental increase in t_L ; it is the wedge between the gross wage (equal to the value marginal product of labor) and the net wage (equal to the marginal social cost of labor in terms of foregone leisure), multiplied by the reduction in labor supply⁶. The denominator is marginal tax revenue (from differentiating $t_L [L + S(H)]$). So this first term is the marginal deadweight loss per dollar of revenue, and the MCPF includes both the

⁶ We will assume that labor supply is not backward-bending.

“direct” cost (equal to unity) of removing revenue from the private sector and the additional deadweight loss created by the distortionary tax⁷.

In reference to Harrington and Portney (1987), Williams (2003) defines environmental damages as the sum of two terms, the respective values of the direct utility loss from reduced health and the time lost to illness⁸ :

$$t_p^w = \frac{1}{I} \frac{\partial U}{\partial H} \frac{\partial H}{\partial Q} - \frac{\partial S}{\partial H} \frac{\partial H}{\partial Q}$$

Since the representative agent still earns his wage during sick-days, it seems that we should correct the second term in our model. Whereas these sick-days were an equivalent loss of purchasing power in Williams (2003), this loss is partially offset by the social security system we have defined. In fact, households only bear the distortionary cost introduced by the government transfers, that is the marginal deadweight loss of the labor tax relative to the wage-keeping device. In this way, the Pigovian rate is given by :

$$t_p = \frac{1}{I} \frac{\partial U}{\partial H} \frac{\partial H}{\partial Q} - (h-1) \frac{\partial S}{\partial H} \frac{\partial H}{\partial Q} \quad (10)$$

Armed with these two definitions, we can now approach the welfare effect of a change in t_D , the government budget constraint being adjusted by t_L . Analogous to the procedure in BMPG (see Appendix for derivation), the welfare effect of the environmental tax can then be expressed as :

$$\frac{1}{I} \frac{dU}{dt_D} = \underbrace{(t_D - t_p) \frac{dD}{dt_D}}_{dW^P} + \underbrace{(h-1) \left(D + t_D \frac{dD}{dt_D} \right)}_{dW^R} - \underbrace{h \left[t_L \frac{\partial l}{\partial t_D} + \left(t_M + \frac{\partial S}{\partial H} \frac{\partial H}{\partial M} \right) \frac{dM}{dt_D} \right]}_{dW^I} - \underbrace{\left[\frac{\partial S}{\partial H} \frac{\partial H}{\partial Q} + h t_L \frac{\partial l}{\partial Q} \right] \frac{dQ}{dt_D}}_{dW^{IB}}$$

(11)

⁷ This is a partial equilibrium definition of the MCPF since it ignores all effects outside the labor market. “Indirect” effects of this tax on goods market – especially on subsidized consumptions – are actually not taken into account with this definition, neither are the changes in revenues from the corrective tax and environmental quality.

⁸ The gross wage has been normalized to equal one.

Expression (11) decomposes the welfare impact of the policy change into four components. The first is the primary or Pigovian effect, dW^P , that is the effect of the tax on the pollution externality. This is the partial equilibrium reduction in D from a marginal increase in the environmental tax, multiplied by the wedge between marginal social cost and the demand price, or marginal social benefit. In a first-best world without preexisting distortions, the optimum is reached for $t_D = t_P$, meaning that the optimal environmental tax must equal the Pigovian rate.

The second term is the gain from the marginal revenue-recycling effect, dW^R . This is the welfare gain from using the pollution tax revenues to reduce the labor tax, relative to when they are returned lump-sum and have no efficiency consequences. So dW^R is the product of the efficiency value per dollar of revenue (the marginal excess burden of taxation) and the incremental pollution tax revenue (from differentiating $t_D D$).

The third and fourth terms, dW^I and dW^{IB} , are respectively what Williams (2003) calls cost-side and benefit-side tax interaction effects. They result when changes in households' labor supply decisions interact with the labor market distortion. For the first one, the pollution tax drives up the price of consumer (polluting) goods, lowering the real wage and consequently discouraging labor supply. As we have seen, this fall in labor supply exacerbates the “private” social cost of the labor tax by $t_L \frac{\partial l}{\partial t_D}$. This also reduces labor tax revenues by $t_L \frac{\partial l}{\partial t_D}$, thus requiring a compensating increase in the labor tax rate and creating an efficiency loss – equal to the amount that the government has to refund multiplied by the efficiency cost per dollar of labor tax revenue (i.e. the marginal excess burden of labor taxation). The tax interaction effect identified by prior literature on the double dividend hypothesis is exclusively the welfare loss from these two impacts, that is $h t_L \frac{\partial l}{\partial t_D}$. In our analysis, there is however a second term in the cost-side tax interaction expression.

This term, which symbolizes interactions between medical expenditures and environmental taxation, can be explained with a similar approach. First, any fall in medical

expenditures generates an efficiency gain, $(h - 1) t_M \frac{dM}{dt_D}$, related to the contraction of subsidies' amount. Second, subventions cause this consumption to be underpriced relative to its social cost. As a result, any decrease in medical expenditures will lead to a general-equilibrium welfare gain. This gain equals the wedge between supply and demand prices (respectively marginal social cost and benefit) multiplied by the reduction of subsidized consumption, that is $t_M \frac{dM}{dt_D}$. Summing these two elements for the effect of the pollution tax on medicines consumption give the second term in square brackets⁹.

Finally, benefit-side tax interaction effect, dW^{IB} , expresses the impact of improved environmental quality on labor supply decisions. In opposition to Williams (2003), a rise in sick-days do not imply a decrease in government revenues. This difference is due to the wage-keeping hypothesis, which has for implicit consequence to enlarge the tax base of the labor tax : more concretely, t_L is levied on $L + S(H)$ instead of effective labor income L^{10} . As a result, welfare impacts of sick-days reduction can be resumed by the product of that decrease and the sum of the efficiency gain and the “private” social benefit relative to that decrease (equal to the wedge between labor marginal social benefit and the price of sick-days, i.e. the cost of the transfer $S(H)$)¹¹. A similar sum as for cost-side tax interaction effect $h t_L \frac{\partial l}{\partial t_D}$ gives the last term of benefit-side tax interaction expression, $h t_L \frac{\partial l}{\partial Q}$.

⁹ In our model, a decrease in medical expenditures may deteriorate the health condition of the representative agent, and therefore increase sick-days. In that case, the positive effect of the decrease in medical expenditures on government budget would be partially offset by the wage-keeping system.

¹⁰ In Williams' analysis, an increase in sick-days reduces labor tax revenues by $t_L \frac{dS}{dQ}$. Refunding it yields an

efficiency cost equal to $(h - 1) t_L \frac{dS}{dQ}$.

¹¹ i.e. : $[(h - 1) + [1 - (h - 1)]] \frac{\partial S}{\partial H} \frac{\partial H}{\partial Q}$

3. Optimal Tax

Following Williams (2003), we now focus on the two opposite tax interaction effects, dW^I and dW^{IB} . We also consider the neutral assumption that goods C and D are equal substitutes for leisure, allowing equation (11) to be rewritten as (see Appendix for derivation):

$$\frac{1}{I} \frac{dU}{dt_D} = (ht_D - t_P) \frac{dD}{dt_D} - h \left(t_M + \frac{\partial S}{\partial H} \frac{\partial H}{\partial M} \right) \frac{dM}{dt_D} + \left\{ -\frac{\partial S}{\partial H} \frac{\partial H}{\partial Q} - (h-1) \frac{e_{LI}}{e_L} \left[1 - (1-t_M) \frac{\partial M}{\partial I} \right]^{-1} (1-t_M) \frac{\partial M}{\partial Q} \right\} \frac{dQ}{dt_D} \quad (12)$$

The first term combines the primary welfare effect with the revenue-recycling effect and the first component of cost-side tax interaction effect. Without the other terms on the right-hand side, it confirms that the optimal environmental tax is equal to the Pigovian rate divided by the MCPF. The second term symbolizes the interactions we have already identified between subsidies to medical expenditures and environmental taxation. Finally, the last term shows that benefit-side tax interaction effects – improved health conditions – may significantly reduce the gross cost of an environmental tax reform, contradicting Williams' conclusions.

In the introduction we have seen that Williams responded to Schwartz and Repetto's intuitions by insisting on an income effect related to the decrease of medical expenditures¹². According to him, this income effect would imply that the increased time available for labor and leisure (sick-days reduction) is rather allocated to the second one. For “typical” parameters – a labor tax rate of 0,4, an uncompensated labor supply elasticity of 0,15 and an

¹² To make the comparison a little bit easier, Williams' conclusions are given by :

$$\begin{aligned} \frac{1}{I} \frac{dU}{dt_D} &= (ht_D - t_P) \frac{dD}{dt_D} + (h-1) \left[-t_L \frac{\partial S}{\partial Q} - \frac{e_{LI}}{e_L} \left(1 - \frac{\partial M}{\partial I} \right)^{-1} \left((1-t_L) \frac{\partial S}{\partial Q} + \frac{\partial M}{\partial Q} \right) \right] \frac{dQ}{dt_D} \\ &= (ht_D - t_P) \frac{dD}{dt_D} + (h-1) \left\{ \left[\left(1 - \frac{\partial M}{\partial I} \right)^{-1} 0,6 - 0,4 \right] \frac{\partial S}{\partial Q} + \left(1 - \frac{\partial M}{\partial I} \right)^{-1} \frac{\partial M}{\partial Q} \right\} \frac{dQ}{dt_D} \end{aligned}$$

with $e_{LI} = -0,15$, $e_L = 0,15$ and $t_L = 0,4$

income elasticity of labor supply of -0,15 – the last term of Williams’ equation (11) (see footnotes) is actually negative : interactions that were presumed positive in fact introduce an additional distortion.

It seems that we cannot draw the same conclusions in this paper. For the same typical parameters, the sign of benefit-side tax interaction effects stays undetermined¹³ because $-\frac{\partial S}{\partial H} \frac{\partial H}{\partial Q}$ is positive.. As we have seen, this term represents the welfare gain due to the reduction of social transfers relative to the wage-keeping device. Finally, the better the global health condition of the agent is, the more he works : the improvement of his health condition would imply the homogenization of his revenue, substituting $S(H)$ by L . Moreover, we can notice that the income effect highlighted by Williams (2003) is somewhat inferior in our model; for $t_M = 100\%$, this income effect disappears and benefit-side tax interaction effects are unquestionably positive. It should be furthermore noticed that these conclusions have a much larger scope than Williams’, as they are independent of the level of labor taxation.

To conclude, it appears that Williams’ results can be reversed. Indeed, if the negative income effect due to the reduction of transfers $S(H)$ is superior to the positive income effect due to the reduction of medical expenditures, then the substitution of $S(H)$ by L implies that the optimal environmental tax rate is greater than traditionally highlighted by BMPG models.

IV. Conclusions

This paper has employed the same methodology as in BMPG analysis to examine the double dividend hypothesis. Using a very close model to Williams’ (2003), it however shows that there may be an efficiency gain related to pollution taxation in most developed¹⁴ countries, so that the optimal environmental tax rate might exceed marginal damages (or Pigovian rate). This contradicting result is mainly due to both hypothesis that have been introduced, that is the existence of subsidies to medical expenditures and the wage-keeping

¹³ as sum of two opposite terms.

¹⁴ or maybe “Welfare State countries”.

device. As explained above, this (simplified) social security system tends to magnify benefit-side tax interactions, which could finally offset cost-side ones.

Prior research has indeed essentially focused on cost-side tax interaction effects to disqualify the double dividend hypothesis, thus neglecting the different channels through which an environmental tax reform may yield a double-dividend¹⁵. Even if it only deals with an additional hypothesis, this paper has tried to show that it is a crucial point in the double dividend debate, *a fortiori* in studies modeling health effects in the agent's utility function. As well as introducing labor market imperfections in models that deal with the possibility of obtaining a second dividend in the form of a reduced unemployment level¹⁶, assuming the existence of a social security system seems also necessary to correctly estimate double dividend prospects in *explicitly modeling health* studies.

¹⁵ This is the sense to give to Williams' (2002) conclusion : "future studies should consider the benefit-side tax interactions as well as the cost-side tax interactions in estimating the optimal level of regulation and the potential gains from such regulation. Studies that fail to consider these second-best effects could prove to be substantially misleading".

¹⁶ See for example Bovenberg and Van der Ploeg (1996), or Chiroleu-Assouline and Lemiale (2001).

Appendix

- **Derivation of equation (11)**

Taking a total derivative of utility with respect to the corrective tax t_D , substituting in consumer first-order conditions, and for constant public spending ($dG = 0$), we obtain the following relation :

$$\frac{1}{I} \frac{dU}{dt_D} = \frac{dC}{dt_D} + (1 + t_D) \frac{dD}{dt_D} + (1 - t_L) \frac{dl}{dt_D} + (1 - t_M) \frac{dM}{dt_D} + \frac{1}{I} \frac{\partial U}{\partial H} \frac{\partial H}{\partial Q} \frac{dQ}{dt_D} \quad (\text{A.1})$$

Summing total derivatives with respect to t_D of the production function (6) and household time constraint (5), and using $dT = 0$, gives the equation :

$$\frac{dC}{dt_D} + \frac{dD}{dt_D} + \frac{dM}{dt_D} + \frac{dl}{dt_D} + \frac{\partial S}{\partial H} \left(\frac{\partial H}{\partial M} \frac{dM}{dt_D} + \frac{\partial H}{\partial Q} \frac{dQ}{dt_D} \right) = 0 \quad (\text{A.2})$$

Substituting A.2 into A.1, and deriving equation (3) with respect to t_D , we find with the help of definitions (9) and (10) :

$$\frac{1}{I} \frac{dU}{dt_D} = (t_D - t_P) \frac{dD}{dt_D} - t_L \frac{dl}{dt_D} - \left(t_M + \frac{\partial S}{\partial H} \frac{\partial H}{\partial M} \right) \frac{dM}{dt_D} + (h - 2) \frac{\partial S}{\partial H} \frac{\partial H}{\partial Q} \frac{dQ}{dt_D} \quad (\text{A.3})$$

We then try to make the term $\frac{dl}{dt_D}$ more explicit. This term symbolizes interactions between the environmental tax and household labor supply decisions. According to the uncompensated demand equations and since the government adjusts its budget constraint with t_L (i.e. $\frac{dt_M}{dt_D} = 0$), we can write :

$$\frac{dl}{dt_D} = \frac{\partial l}{\partial t_D} + \frac{\partial l}{\partial t_L} \frac{dt_L}{dt_D} + \frac{\partial l}{\partial Q} \frac{dQ}{dt_D} \quad (\text{A.4})$$

Taking a total derivative with respect to t_D of the government budget constraint (8) and with the help of (5), we find, for $dG = dT = 0$:

$$\frac{dt_L}{dt_D} = - \frac{1}{L + S(H)} \left[D + t_D \frac{dD}{dt_D} - t_M \frac{dM}{dt_D} - t_L \frac{dl}{dt_D} - \frac{\partial S}{\partial H} \left(\frac{\partial H}{\partial M} \frac{dM}{dt_D} + \frac{\partial H}{\partial Q} \frac{dQ}{dt_D} \right) \right] \quad (\text{A.5})$$

This expression gives the reduction in labor tax that can be financed by a marginal increase in the environmental tax, while maintaining budget balance. Replacing it in **A.4** gives:

$$\frac{dl}{dt_D} = \frac{[L + S(H)] \frac{\partial l}{\partial t_D} - \frac{\partial l}{\partial t_L} \left[D + t_D \frac{dD}{dt_D} - t_M \frac{dM}{dt_D} - \frac{\partial S}{\partial H} \left(\frac{\partial H}{\partial M} \frac{dM}{dt_D} + \frac{\partial H}{\partial Q} \frac{dQ}{dt_D} \right) \right] + [L + S(H)] \frac{\partial l}{\partial Q} \frac{\partial Q}{\partial t_D}}{L + S(H) - t_L \frac{\partial l}{\partial t_L}} \quad (\text{A.6})$$

Finally, substituting **A.6** into **A.3** gives equation **(11)**.

- **Derivation of equation (12)**

Taking a total derivative of utility with respect to t_L , holding the levels of public spending, utility and environmental quality constant, and substituting in the consumer first-order conditions yields :

$$\frac{\partial l^c}{\partial t_L} = \frac{1}{1-t_L} \frac{\partial C^c}{\partial (1-t_L)} + \frac{(1+t_D)}{1-t_L} \frac{\partial D^c}{\partial (1-t_L)} + \frac{(1-t_M)}{1-t_L} \frac{\partial M^c}{\partial (1-t_L)} \quad (\text{A.7})$$

where the superscript “c” denotes a compensated derivative.

The assumption that the cross elasticity of D and leisure is equal to the average (weighted by consumption shares) over all goods is given by :

$$e_{D,l} = S_D e_{D,l} + S_C e_{C,l} + S_M e_{M,l} \quad (\text{A.8})$$

where $e_{i,l}$ and S_i ($i = C, D, M$) respectively represent the compensated elasticity of demand for good i with respect to the price of leisure and the share of that good i in total consumption¹⁷. Substituting **A.8** and the household budget constraint **(7)** into **A.7** yields after some manipulations :

$$\frac{\partial l^c}{\partial t_L} = \frac{\partial D^c}{\partial (1-t_L)} \frac{[L + S(H)]}{D} \quad (\text{A.9})$$

¹⁷ Formally : $e_{i,l} = \frac{\partial i^c}{\partial (1-t_L)} \frac{1-t_L}{i}$ and $S_i = \frac{p_i i}{\sum (p_i i)}$

As changes in the price of leisure and polluting goods are equal to changes in their respective tax rates the Slutsky equations give :

$$\frac{\partial l}{\partial t_D} = \frac{\partial l^c}{\partial t_D} - \frac{\partial l}{\partial I} D \quad (\text{S.1})$$

$$\frac{\partial l}{\partial t_L} = \frac{\partial l^c}{\partial t_L} - \frac{\partial l}{\partial I} [L + S(H)] \quad (\text{S.2})$$

According to (11) and (S.1), we have :

$$dW^I = -h \left[t_L \left(\frac{\partial l^c}{\partial t_D} - \frac{\partial l}{\partial I} D \right) + \left(t_M + \frac{\partial S}{\partial H} \frac{\partial H}{\partial M} \right) \frac{dM}{dt_D} \right]$$

Using the Slutsky symmetry property $\frac{\partial l^c}{\partial t_D} = \frac{\partial D^c}{\partial (1 - t_L)}$, relations S.2 and A.9, we can rewrite cost-side tax interaction effects in a similar fashion than Williams (2003) :

$$dW^I = (1 - h) D - h \left(t_M + \frac{\partial S}{\partial H} \frac{\partial H}{\partial M} \right) \frac{dM}{dt_D} \quad (\text{A.10})$$

As we have seen, the expression for benefit-side tax interaction effects dW^{IB} is :

$$dW^{IB} = - \left[\frac{\partial S}{\partial H} \frac{\partial H}{\partial Q} + h t_L \frac{\partial l}{\partial Q} \right] \frac{dQ}{dt_D} \quad (\text{A.11})$$

According to the household budget constraint (7), the change in spending on C , D and l for a change in Q will equal :

$$(1 - t_L) \frac{\partial l}{\partial Q} + (1 + t_D) \frac{\partial D}{\partial Q} + \frac{\partial C}{\partial Q} = - (1 - t_M) \frac{\partial M}{\partial Q} \quad (\text{A.12})$$

Similarly, for a change in I :

$$(1 - t_L) \frac{\partial l}{\partial I} + (1 + t_D) \frac{\partial D}{\partial I} + \frac{\partial C}{\partial I} = 1 - (1 - t_M) \frac{\partial M}{\partial I} \quad (\text{A.13})$$

Weak separability of health in the utility function implies that leisure demand is determined only by the relative prices of l , C and D and by total spending on those goods. Those relative prices are not affected by changes in Q or changes in I . As a result, the

derivative of l with respect to Q will equal the derivative of l with respect to I times the ratio of the derivative of spending on those goods with respect to Q (A.12) to the derivative of spending on those goods with respect to I (A.13) :

$$\frac{\partial l}{\partial Q} = -\frac{\partial l}{\partial I} \left[1 - (1 - t_M) \frac{\partial M}{\partial I} \right]^{-1} (1 - t_M) \frac{\partial M}{\partial Q} \quad (\text{A.14})$$

Replacing $\frac{\partial l}{\partial Q}$ by its value in A.11, and observing that $h t_L \frac{\partial l}{\partial I} = -(h - 1) \frac{e_{LI}}{e_L}$, we obtain :

$$dW^{IB} = \left\{ -\frac{\partial S}{\partial H} \frac{\partial H}{\partial Q} - (h - 1) \frac{e_{LI}}{e_L} \left[1 - (1 - t_M) \frac{\partial M}{\partial I} \right]^{-1} (1 - t_M) \frac{\partial M}{\partial Q} \right\} \frac{dQ}{dt_D} \quad (\text{A.15})$$

where e_L is the uncompensated labor supply elasticity, and e_{LI} is the income elasticity of labor supply¹⁸.

Substituting in expression (11) the values of dW^I and dW^{IB} given by A.10 and A.15 gives equation (12).

¹⁸ That is : $e_L = \frac{\partial [L + S(H)]}{\partial (1 - t_L)} \frac{(1 - t_L)}{[L + S(H)]} = \frac{\partial l}{\partial t_L} \frac{1 - t_L}{L + S(H)}$

and $e_{LI} = \frac{\partial [L + S(H)]}{\partial I} \frac{(1 - t_L)[L + S(H)]}{[L + S(H)]} = -\frac{\partial l}{\partial I} (1 - t_L)$

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